Staff Summary Sheet

	To	Action	Signature (Surname), Grade, Date		To	Action	Signature (Surname), Grade, Date
1	DFEM	Approve	(Rhymer) LtCol 3 Jun 14	6			
2	DFER	Review	Sa??, AD22, 3 Sep 14	7			
3	DFEM	Action		8			
4				9			
5				10			

Grade and Surname of Action Officer	Symbol	Phone	Suspense Date
AD-24/Jensen	DFEM	333-7946	14 June 2014
Subject Clearance of Material for Public Release — Case Number: To be Assigned			**SSS Date** 27 May 2014

Summary

USAFA-DF-PA-360

1. Purpose: To provide security and policy review on the document at Tab 1 prior to release to the public.

2. Background:

- *Author(s)*: Mr Chris Hamon, Mr Brock Dunlap, Mr. Bradley Adam Camburn (University of Texas, Austin), Dr Matt Green, (LeTourneau Univ.), Dr. Daniel D. Jensen (U.S. Air Force Academy), Dr. Richard H. Crawford (University of Texas, Austin)

- *TITLE*: Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool

- *Abstract*:

A new prototyping planning tool guides designers in choosing between virtual vs. physical prototyping strategies based on answers to Likert-scale questions. We developed this tool to augment prior work in design methods seeking to facilitate prototyping strategy development. This new tool was tested in a pilot experiment with engineering students individually tasked with optimizing the design of a four-bar linkage. All students were given a design problem that involved designing a four-bar linkage to be used to draw a specific shape. The students were then instructed to use the new prototyping planning tool to decide whether to create a virtual or physical prototype of a four-bar linkage, with the goal of maximizing the performance metric detailed in the design problem statement. This paper describes the new prototype strategy planning tool, the pilot experiment, and results and conclusions. The very encouraging pilot results provide a template and strong motivation for conducting a larger scale experiment with a sample size leading to statistically significant findings.

- *Release information*: Standard release of a USAFA technical report.

- *Previous clearance information*: N/A.

- *Recommended distribution statement*: Distribution A, Approved for public release, distribution unlimited.

3. Discussion:

To be published in *Proceedings of the Annual Conference- American Society of Engineering Education*

4. Recommendation: Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

Daniel D Jensen

DANIEL D. JENSEN, PhD, USAF
Department of Engineering Mechanics

1 Tab
Article, Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool

Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool

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Virtual or Physical Prototypes?
Development and Testing of a Prototyping Planning Tool

Abstract

A new prototyping planning tool guides designers in choosing between virtual vs. physical prototyping strategies based on answers to Likert-scale questions. We developed this tool to augment prior work in design methods seeking to facilitate prototyping strategy development. This new tool was tested in a pilot experiment with engineering students individually tasked with optimizing the design of a four-bar linkage.

All students were given a design problem that involved designing a four-bar linkage to be used to draw a specific shape. The students were then instructed to use the new prototyping planning tool to decide whether to create a virtual **or** physical prototype of a four-bar linkage, with the goal of maximizing the performance metric detailed in the design problem statement. This paper describes the new prototype strategy planning tool, the pilot experiment, and results and conclusions. The very encouraging pilot results provide a template and strong motivation for conducting a larger scale experiment with a sample size leading to statistically significant findings.

1 Introduction

An engineering *prototype* (physical or virtual) is an initial manifestation of a design concept, either a scale or full-size model of a structure or piece of equipment, which can be used to evaluate performance, form, and/or fit. *Prototyping* is the process of generating prototype(s), usually between concept generation and design verification stages. Prototypes provide design engineers the opportunity to: determine if a concept is technically feasible, optimize performance, understand interfaces between subsystems, and/or identify potential assembly and manufacturing issues. In addition, prototypes serve as an effective method of communicating the functionality and/or progress of a design concept, to both technical and non-technical audiences. For these reasons prototyping is an integral part of the product development process.

Prototypes may be physical or virtual. A *physical prototype* is the preliminary embodiment of a design concept in a tangible model. Physical prototypes may be fully or partially functional, and allow for sensory evaluation of the concept, possibly including aesthetics and ergonomics. In contrast, *virtual prototypes* are digital mock-ups (computer simulations and/or analytical models) of physical products that can be analyzed, tested, and presented in order to serve the principal purposes of prototyping in the product development process. Computational advances have vastly expanded the possibilities of virtual prototyping in the past few decades. Practical examples of virtual prototyping techniques include 3D CAD models with motion analysis, finite element analysis, manufacturability evaluations, and/or computational fluid dynamics (CFD.) A lack of tangible interaction and evaluation distinguishes virtual prototypes from physical prototypes[1]. Both virtual and physical prototypes may be developed for an entire system or a specific subsystem.

2 Background

Prototyping is a vital component in the product design process as a whole. A *prototyping strategy* refers here to *the set of choices guiding development of prototype(s)*[2]. A general prototyping strategy (such as "one should prototype multiple concepts early") leads to a *project-specific* prototyping strategy (such as "prototype concepts A, D, and E by week #3.") Most currently published structured prototyping approaches (strategies) focus on management logistics aspects such as lead times, budgets, and project efficiency[3]. However, Otto and Wood[4] provide a foundation for an engineering approach to prototyping strategy in the form of a basic method for designing physical prototypes and guidelines for prototype development. Additionally, Otto and Wood cover analytical (virtual) and physical prototyping techniques and appropriate testing procedures to ensure that physical models satisfy design requirements. The authors acknowledge that virtual modelling is important in the prototyping process, but they recommend that designers must ultimately develop and test *physical* prototypes for the successful instantiation of design concepts.

Recently a diverse research team presented work towards generalized methodologies for developing *project-specific prototyping strategies*[5]. This methodology simply translates the context of a specific design problem into prototyping decisions, yielding a project-specific prototyping strategy. In other words, the prototyping strategy formation methodology uses the independent variables of a design problem (e.g. available budget/time, difficulty in meeting design requirements, and designer's experience) in order to derive dependent prototyping strategy variables (e.g. number of prototypes to build, prototype scaling, and subsystem isolation). These dependent strategy variables, representing many critical prototyping decisions, were amalgamated from heuristics for prototyping best practices outlined by Moe[6], Christie[7], and Viswanathan[8]. This prototyping strategy formation method provides a systematic framework to translate independent context variables into dependent prototyping strategy variables in the following four steps (Figure 1):

1. Predict how many iterations each concept requires to satisfy design requirements (in light of: designer's experience, design requirement difficulty, and design requirement rigidity.)
2. Determine appropriate prototype scaling, subsystem isolation, and functional relaxation for each iteration of each concept (diagrammatic flowcharts aid this step.)
3. Determine which concepts to prototype in parallel, based on available budget and time.
4. Document the resulting prototyping strategy.

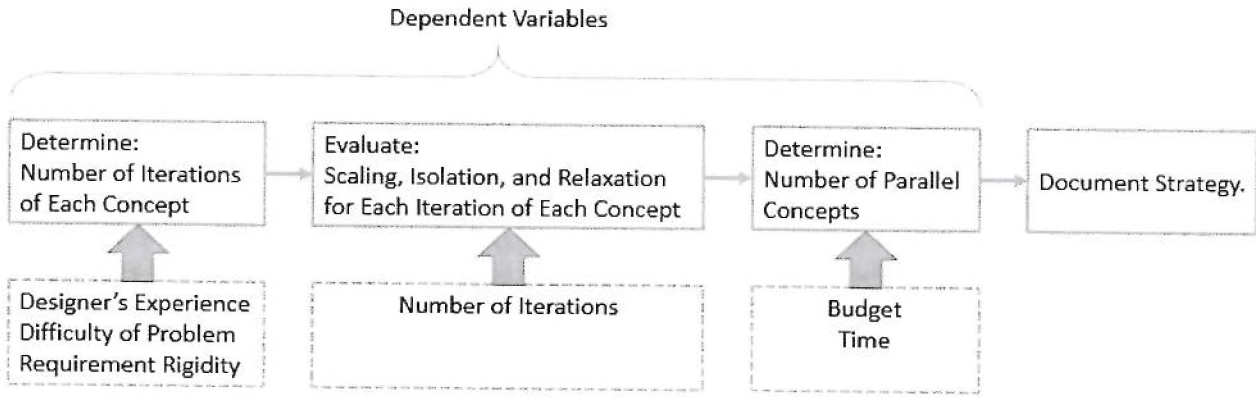

Figure 1: Flowchart of Prototyping Strategy Method[5]

The above methodology was previously experimentally evaluated in a controlled design environment using primarily mechanical engineering students[5]. The published experiment results indicate using the prototyping strategy formation method above is positively correlated with early-stage design success. Thus, implementing this method can potentially improve design performance while increasing the likelihood of staying within budget and time constraints. The need for more comprehensive prototyping planning and this ground-breaking research on an engineering approach to prototyping strategy formation both motivate and shape the new work presented in this paper.

This paper supplements the above prototyping strategy formation method pioneered by Camburn et al. by adding a new prototyping decision – whether a prototype will be virtual or physical. The goal of this study is a systematic decision tool guiding the choice between virtual or physical prototyping for generalized design problems.

No research was located addressing a structured method aiding engineering designers in deciding between virtual and physical prototyping. However, Ulrich and Eppinger[9] detail the usefulness of considering virtual versus physical prototyping in a generalized description of the prototyping process. By charting prototyping decisions in two dimensional space (Figure 2), they provide a graphical decision making tool based on the relative accuracy and expense of virtual versus physical prototypes.

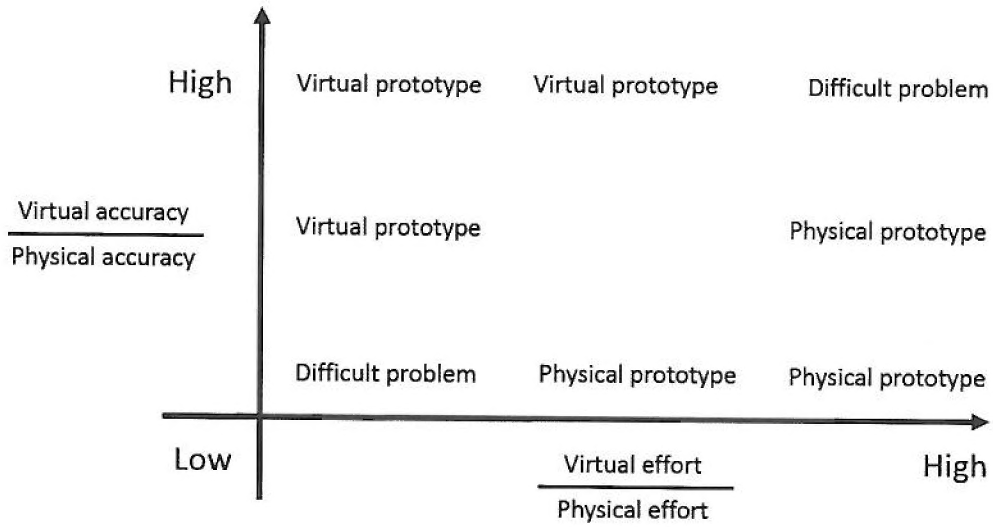

Figure 2: Decision Trade-off between Virtual and Physical Models (Adapted from Ulrich and Eppinger[9])

Ulrich and Eppinger's only caveat is that comprehensive virtual prototypes are generally not feasible. However, there are some instances when physical prototypes are prohibitively expensive. For example, Northrop Grumman[10] has virtually modeled an entire aircraft carrier with over three million parts (Figure 3.) This complex virtual model allows engineers to foresee potential piping layout issues, predict overall buoyancy/draft height/center of mass, and estimate drag forces without constructing a costly physical model.

Figure 3: Virtual Model of Aircraft Carrier (image courtesy Northrup Grumman)[10]

3 Methodology

Choosing between a virtual or physical prototype is a critical decision in the product design process. Selection of the type of prototype(s) will most likely be determined based on budget and time constraints as well as the experience of a design team. A structured prototyping strategy formation method addressing the choice of virtual or physical prototypes will be a useful addition to the prototyping strategy formation tool developed by Camburn et al.[5] described above.

Therefore, a decision making tool for choosing between virtual and physical prototypes was developed to build upon the existing prototyping strategy formation tool. A major contribution of this work is the use of a heuristics-based approach, rather than the strictly quantitative approach of the prior work. The new virtual-vs-physical module of the prototyping strategy formation method includes a newly developed tool employing Likert-scale questions (Appendix A.)

The pilot experimental study reported here tests this heuristics-based, Likert-scale tool. A classical four-bar linkage design problem was chosen for a controlled experiment based on practical considerations. The feasibility of prototyping four-bar linkages both physically and virtually, with basic materials and easy-to-use software, enables testing of the new virtual vs. physical module of the prototyping strategy formation method.

All eight participants in this pilot experiment were junior or senior mechanical engineering students, with at least basic familiarity with four-bar linkage design. Each participant worked individually. As shown in the experiment worksheet in Appendix A, the experiment began with a five minute introduction. During this time the difference between virtual and physical prototypes was defined. In addition, participants were shown both a graphical depiction and physical example of a four-bar linkage. Next, Grashof's Law was presented in order to inform participants of the condition necessary to achieve continual rotation of the shortest link in a four-bar linkage, i.e., the sum of the shortest and longest links must be less than the sum of the other two links.

Participants were then instructed to complete an initial Likert-scale survey (Appendix A), and record their familiarity with four-bar linkages, experience using computer simulation software, experience building physical models, and preference of using software versus building physical models. Next, creating a virtual four-bar linkage using GIM[11],[12] software was briefly detailed. The free (with registration) GIM software provides an easy interactive environment for the design and simulation of simple linkages (Figure 4.)

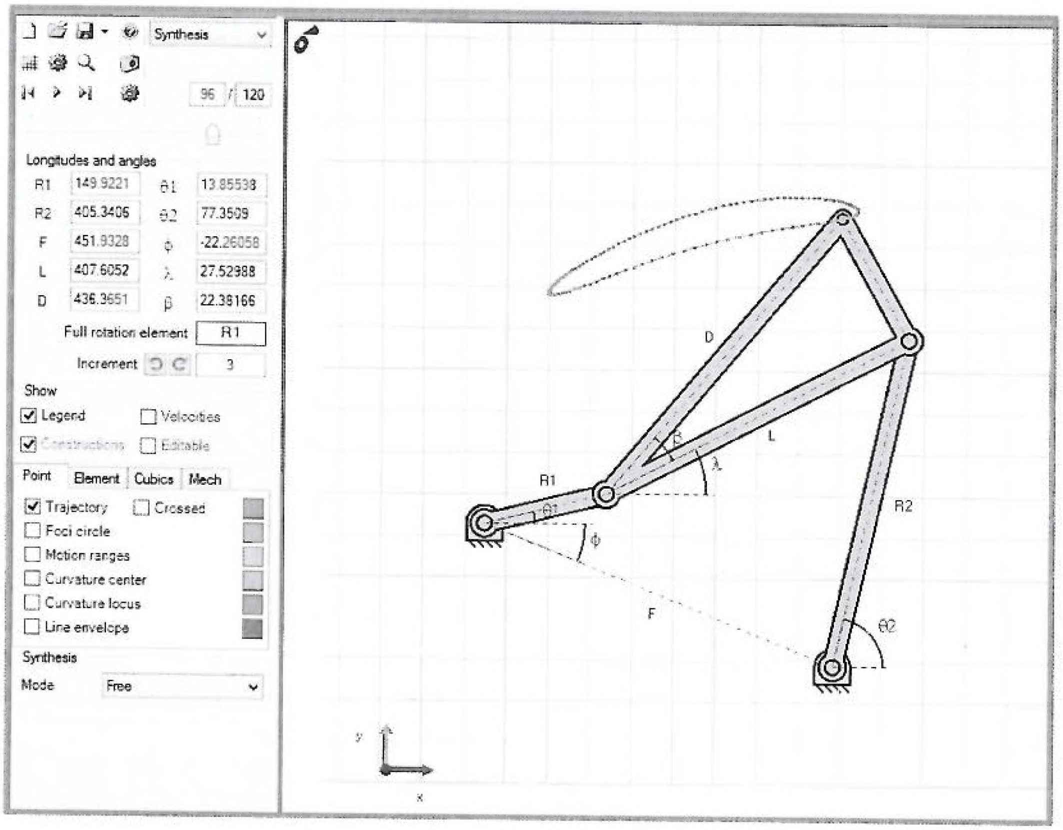

Figure 4: GIM Software User Interface

After a brief demonstration of the GIM software, participants were presented with the following materials and tools (Figure 5) to potentially construct a physical four-bar linkage:

- Four precut foam board pieces
- Four detachable pins
- Hole-punch (for installing detachable pins)
- Scissors (for cutting foam board to the desired length)
- Pencil and paper (for marking the trajectory of a four-bar linkage)

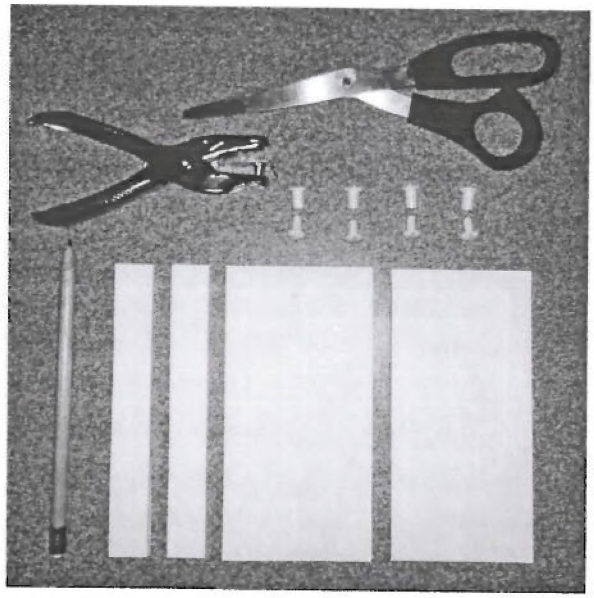

Figure 5: Materials for Four-bar Linkage Physical Modelling, Excluding Paper

Participants were then presented with the problem of designing a continuously rotating four-bar linkage to draw the longest possible horizontal shape (the closest approximation of a straight line). The design objective is to maximize $\Delta X / \Delta Y$ (Figure 6.) Participants were permitted an unlimited number of modifications within a 30 minute time limit.

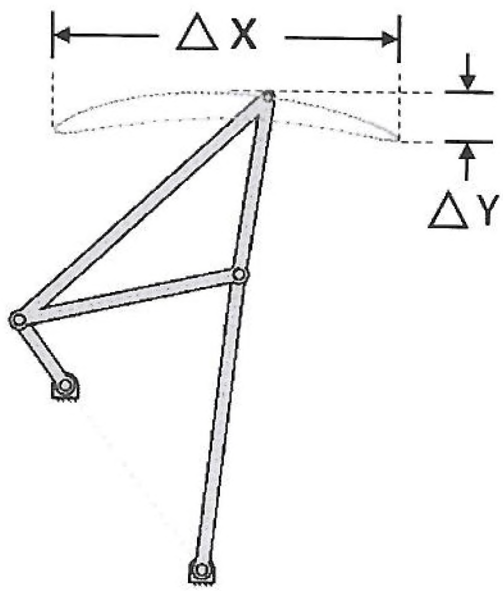

Figure 6: Depiction of Performance Metric: Maximize $\Delta X / \Delta Y$

After participants had an understanding of the design problem and the process for creating both virtual and physical four-bar linkage prototypes, they were instructed to complete a second

Likert-scale survey (Figure 7.) Based on the sum of their survey responses (bottom of Figure 7), participants then chose to either virtually or physically prototype a four-bar linkage in order to achieve the design objective.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping will require less time than building physical prototype(s).					
b)	Virtual prototyping will be sufficiently accurate to model critical physics or dynamic motions.					
c)	Prototyping a four-bar linkage will require many iterations.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical				Virtual →

Figure 7: Likert-scale Survey for Informing Choice between Virtual and Physical Prototyping

The Likert-scale in Figure 7 expands upon Ulrich and Eppinger's two-axis graph of suggested choices based on the *relative accuracy* of virtual with respect to physical models versus the *relative effort* of virtual with respect to physical models. Question (a) addresses participants' perception of the ratio of accuracy between virtual and physical models, and question (b) addresses the ratio of effort between virtual and physical models. Question (c) has the designer consider the number of design iterations to address the relative ratio of both effort and time of virtual compared to physical models. Participants use the sum of their responses to choose which type of prototype to create.

Participants who chose virtual prototyping received a short (<5 min.) GIM software tutorial, while those choosing physical prototyping received a brief (<5 min.) demonstration of physical construction with the provided materials. Each participant recorded their prototyping start and end times with a maximum of 30 minutes allowed.

Finally, after completion of either a virtual or physical prototype, all participants completed an exit survey. The exit survey recorded participants' opinion of the choices they made and of the Likert-scale as a decision making tool.

4 Results

Two out of the eight participants in this pilot study chose to create a physical prototype of their four-bar linkage, and Figure 8 pictures an example being used to draw a pencil line on paper.

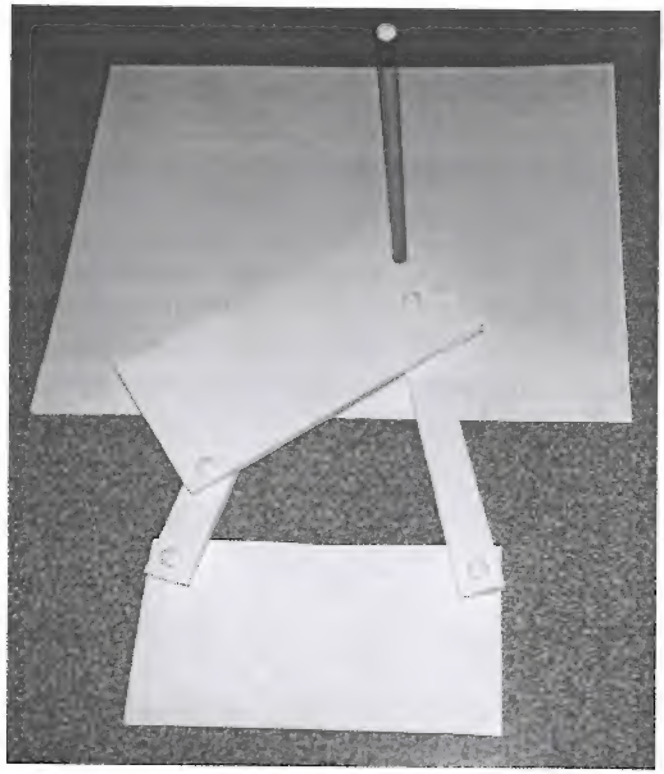

Figure 8: Example of Four-bar Linkage Physical Prototype, with Pencil to Draw a Line on Paper

Participants choosing virtual prototyping achieved $\Delta X / \Delta Y$ ratios on average six times higher than participants using physical prototypes. One additional participant not included here was assigned (rather than given a choice) to physically prototype, and outperformed the physical prototypers in this study by a factor of 3 (achieving a $\Delta X / \Delta Y = 9.5$, although still less than the 21.6 average of the six virtual prototypes.) This exploratory pilot experiment with a small sample size is intended to guide design of a larger experiment with more statistically robust results.

Table 1 presents a summary of the data obtained in this pilot experimental study, including the $\Delta X / \Delta Y$ ratio performance metrics and time to complete prototyping. Appendix B presents more detailed data.

Table 1: Summary of Experiment Data

		Average: Virtual	Average: Physical	Delta (V-P)
Initial Survey	I have an understanding of four-bar linkages	0.8	1.0	-0.2
	I have experience using software	1.3	0.5	0.8
	I prefer to design using software	0.7	-1.0	1.7
	I have experience building physical models	0.7	1.5	-0.8
Likert Scale	VP will require less time than PP	0.7	0.0	0.7
	VP will be sufficiently accurate	1.3	0.0	1.3
	Prototyping a four-bar linkage will require many iterations	1.2	-1.0	2.2
Exit Survey	VP is the best technique for designing four-bars	1.7	0.0	1.7
	GIM is a useful tool for VP four-bars	1.7	0.5	1.2
	Likert Scale was useful in choosing VP or PP	0.7	0.0	0.7
	I will consider using VP in future designs	1.7	1.5	0.2
	I chose the best technique for my prototype	**1.7**	**-1.5**	3.2
	Time to Complete (minutes)	**21**	**26**	**-5**
	Performance Ratio (ΔX / ΔY)	**21.6**	**3.5**	**18.2**

5 Conclusions and Future Work

This pilot study, itself a prototype for future experiments, provides insight into development of a tool aiding designer choice between virtual and physical prototypes. This paper presents a Likert-scale guide to choosing virtual vs. physical prototyping, which can be a useful addition to a larger prototyping strategy formulation method such as that proposed by Camburn et al[5]. It is not the intention of this small sample size pilot to make statistical claims, but rather to demonstrate the viability of the experiment and provide a foundation and compelling motivation to conduct it on a much larger scale.

Future work will improve the experiment detailed in this paper and obtain results for a larger sample size. In addition, testing this method with new design problems, in which the choice between virtual and physical models is not obvious, will provide more generalizable results. Potential design problems must use simple and readily-available computer software for practical reasons.

Additional research will seek deeper understand of what designers learn from tactile engagement while building physical prototypes (such as fit and form), in contrast to the virtual experience of

software manipulations. Incorporating the importance of human-prototype interaction as a heuristic in decision making may enhance prototyping strategies.

Finally, investigating any potential correlations between MBTI types of participants and virtual vs. physical preference and performance outcomes might lead to the development of additional heuristics.

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The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the [funding agency names temporarily removed for blind review.]

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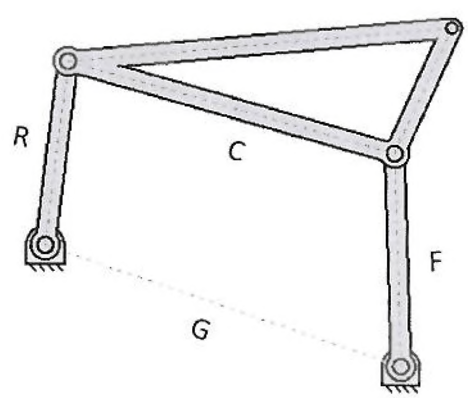
Appendix A: Experiment Worksheet

Name: ______________________________ Date: ________________________

Four-Bar Linkages
Virtual or Physical Prototyping Experiment

1. Introduction to four-bar linkages:

- Grashof's Law: (shortest link + longest link) < (sum of remaining 2 links)
- Virtual Prototype - a computer simulation (CAD model, motion analysis, FEA, CFD, etc.) of a product that can be analyzed, tested, and modified.
- Physical Prototype – a tangible, physical model of a product that can be analyzed, tested, and modified.



R = rocker link
G = ground link
F = follower link
C = coupler link

2. Fill out initial survey:
Based on your experience, complete this survey.

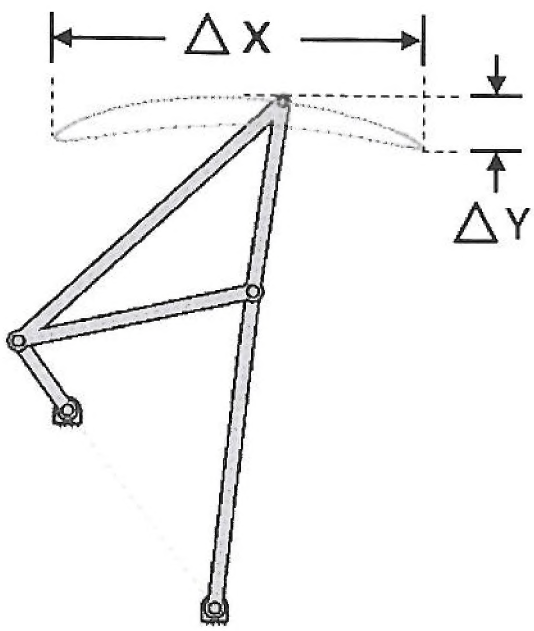
		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	I have an understanding of four-bar linkages.					
b)	I have experience using computer simulation software (e.g., CAD, FEA, etc.).					
c)	I prefer to design using software, rather than building physical models.					
d)	I have experience building physical models.					

3. **Introduction to GIM software**

4. **Prototype four-bar linkage:** [maximum 30 minutes]

Design Problem:

- Design a continuously rotating four-bar linkage to draw the longest possible horizontal shape.
- Goal: maximize the ratio of ΔX / ΔY
- Complete Likert Scale below and choose to virtually **or** physically prototype a four-bar linkage.
- There is no limit to the number of times you may modify your design.
- Record your Starting and Completion Time below.



Starting Time:

Completion Time:

4. b) Complete Likert Scale:

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping will require less time than building physical prototype(s).					
b)	Virtual prototyping will be sufficiently accurate to model critical physics or dynamic motions.					
c)	Prototyping a four-bar linkage will require many iterations.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical			Virtual →	

5. **Fill out exit survey:**

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping (vs. physical prototyping) is the best technique for designing four-bar linkages.					
b)	GIM software is a useful tool for virtually prototyping four-bar linkages.					
c)	The Likert Scale above was useful in choosing between virtual and physical.					
d)	I will consider using virtual prototyping in future designs.					
e)	I chose the best technique for my prototype.					

f) Why did you choose virtual or physical prototyping?

6. Submit your physical prototype,
or email your virtual prototype file (FirstName_LastName.gim) to **[researcher email address]**

Appendix B: Experimental Data

	Participant	1	2	3	4	5	6	7	8	Average: Virtual	Std Dev.: Virtual	Average: Physical	Std Dev.: Physical	Average Delta (V-P)
	Virtual or Physical	V	V	V	V	V	V	P	P					
Initial Survey	I have an understanding of four-bar linkages	1	1	1	1	0	1	2	0	0.8	0.4	1.0	1.0	-0.2
Initial Survey	I have experience using software	2	1	1	2	1	1	0	1	1.3	0.5	0.5	0.5	0.8
Initial Survey	I prefer to design using software	1	1	-1	2	0	1	0	-2	0.7	0.9	-1.0	1.0	1.7
Initial Survey	I have experience building physical models	-1	-1	2	1	2	1	2	1	0.7	1.2	1.5	0.5	-0.8
Likert Scale	VP will require less time than PP	0	1	1	1	0	1	1	-1	0.7	0.5	0.0	1.0	0.7
Likert Scale	VP will be sufficiently accurate	2	1	1	2	2	0	0	0	1.3	0.7	0.0	0.0	1.3
Likert Scale	Prototyping a four-bar linkage will require many iterations	1	1	1	1	2	1	-1	-1	1.2	0.4	-1.0	0.0	2.2
Exit Survey	VP is the best technique for designing four-bars	2	2	2	2	2	0	-1	1	1.7	0.7	0.0	1.0	1.7
Exit Survey	GIM is a useful tool for VP four-bars	2	2	1	2	2	1	0	1	1.7	0.5	0.5	0.5	1.2
Exit Survey	Likert Scale was useful in choosing VP or PP	1	0	0	1	2	0	0	0	0.7	0.7	0.0	0.0	0.7
Exit Survey	I will consider using VP in future designs	2	2	1	2	2	1	2	1	1.7	0.5	1.5	0.5	0.2
Exit Survey	I chose the best technique for my prototype	2	2	2	2	2	0	-2	-1	1.7	0.7	-1.5	0.5	3.2
	Time to Complete (minutes)	**20**	**19**	**20**	**22**	**23**	**22**	**25**	**27**	**21**	**1.4**	**26**	**1.0**	**-5**
	Performance Ratio ($\Delta X / \Delta Y$)	**34.2**	**12.7**	**22.1**	**14.5**	**24.6**	**n/a**	**5.2**	**1.7**	**21.6**	**7.7**	**3.5**	**1.8**	**18.2**